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THE APPLICATION OF QUEUEING THEORY TO THE MODELLING OF CP-140 AIRCRAFT COMMUNICATIONS

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ABSTRACT

Several authors have argued that queueing models can be used to predict workload and performance of operators under the single-channel hypothesis of man's information processing capability. This paper used a simple exponential, single-server queueing model to investigate the application of queueing theory to communication and navigation tasks performed aboard the CP-140 Aurora. It was anticipated that the model would provide insight into how individual tasks with low workloads combine to create high workload situations. The results, however, indicated problems originating from the data and the model. A new model was recommended as well as an appropriate data collection technique for the application of queueing theory to multi-task situations.

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1. INTRODUCTION

This report documents an investigation of the applicability of queueing theory to predict operator workload and performance in multi-task situations. Queueing theory is a branch of mathematics that is concerned with the study of waiting lines. Consider the example of a queueing situation in which arriving aircraft wait for access to a runway. The system is characterized by aircraft or *arrivals* that require the use of the runway, a *server*. A queue may develop even if the average time that aircraft require the use of the runway is less than the average time between arrivals of these aircraft. The variability of arrival and service times is the most important aspect of a queueing system. A server does not necessarily have to be a runway, but anything that can be occupied such as a human or a facility. Similarly, arrivals need not be aircraft, but anything that appears at particular times and requires the use of a server. An individual performing tasks is recognized as a *queueing system* because the system consists of arriving tasks that compete for the operator's (server's) attention. These tasks may be thought of as loading the operator (Meister 1985). Tasks waiting to be performed are analogous to waiting aircraft and both an operator and a runway are servers that can be occupied by the arrivals.

Queueing models of human-machine interaction may be applied when an individual must deal with tasks that have varying priorities and performance requirements (Rouse 1980). But what can queueing theory tell us about this type of multi-task situation? The most common use of queueing theory in industry is to provide information from which decisions about the capacity of a system can be based. In the example of waiting aircraft, the average waiting times for varying traffic conditions may be used to select a suitable number of runways. The analogy to a human-machine system is difficult to make, however, as providing additional operators is often an impractical solution to the problem of accomplishing many tasks. Moreover, the focus of this report concerns a single-operator multi-task situation only. Two common measures of the performance of a queueing system are the amount of time that tasks must wait to be performed and the fraction of time that an operator is occupied (*operator utilization*). Operator utilization has been used as a means of evaluating workload, for example, Schmidt (1978) used a queueing model to analyze workload factors affecting the performance of air-traffic controllers. The occupancy of the server, which was the workload component of the model, and the average delay of aircraft were predicted as a function of demand. The queueing investigation in the present report examines this most frequent use of queueing theory in the analysis of human-machine interaction and takes a preliminary look at what other types of information queueing theory can provide about the behavior of operators in multi-task situations.

A study of CP-140 Aurora aircraft communications by Litton Systems Canada Ltd. (Vinnedge 1986) provides the means of conducting the queueing investigation. The role of the Canadian Forces CP-140 Aurora is to perform tactical missions such as anti-submarine warfare, maritime and arctic surveillance and search and rescue missions. Presently, the Aurora is capable of operating jointly with Canadian and NATO task forces including submarines, ships and other aircraft. Because many of Canada's allies are replacing their communication systems with more advanced technology, much of the encryption equipment is rapidly becoming obsolete. The Department of National Defence has been forced to consider the replacement of the communication management system of the CP-140, to ensure continued communication capabilities with Canada's allies. The operational requirements, combined with increasingly sophisticated navigation and communication equipment, will lead to extreme complexities in the crew-system integration. Thus to facilitate total aircraft system effectiveness, Litton Systems Canada Ltd. was commissioned in 1985 to provide human engineering data to assist in determining an optimal functional design for a replacement communication management system.

Litton's examination of the CP-140's communication management system included task, workload, and time-line analyses of four major tactical positions. Crew members provided subjective workload ratings, approximate durations, and estimates of when each task would occur during a standard co-ordinated operations (co-op) mission scenario. Although the workload of individual tasks was estimated as generally low, the aggregate workload of the entire mission was considered extremely high. The co-op mission, for example, was rated as a '6' on a scale from 1-5 by navigation communication (NAVCOM) operators because of the high workload involved during one mission segment, whereas individual tasks during the same segment were rated as approximately '4' on a scale from 1-7. The results of Litton's human engineering study show that operators are capable of achieving satisfactory performance on all tasks during periods of a mission with low workload. During periods when many tasks are imposed on an operator, however, tasks appear to combine to produce a high workload and satisfactory performance is not achieved. As queueing theory is concerned with how an operator co-ordinates a set of tasks, it is reasonable to assume that a queueing model of a CP-140 crew member would provide insight about the affect of combined tasks on operator workload.

Queueing models of human-machine systems have classically described humans as time-shared computers who serially allocate attention to a variety of tasks (Rouse 1980), that is, operators perform tasks one at a time. This report takes the same approach of assuming the operator is a single-channel processor. Although the data collected by Litton were not intended for the application of queueing theory, its availability and the apparent disparity between individual task loadings and overall workload provided the motivation for this investigation. The purpose of the present report is not to assess the communication management system of the CP-140, nor is it to evaluate suitable methods of data collection for queueing theory application. A simple exponential single-server model is used as a fundamental model to assess the potential use of queueing theory, using the aviation environment of the CP-140 Aurora. The intent is to assess the limitations and assumptions involved when applying queueing models to operators in multi-task situations, not to develop a finely tuned model.

2. QUEUEING THEORY

Queueing theory is concerned with the study of waiting lines and may appropriately be applied if one is interested in evaluating system performance measures such as how long customers must wait to be serviced or service times of customers. (Hillier and Lieberman 1986, Phillips, Ravindran and Solberg 1976, Rouse 1980). Queues will form if the demand for service exceeds the capacity of the system to provide service. Queues may also form even if the average arrival rate (demand) of customers is much less than the average service rate (capacity) of the system because of the variability in the rates. The formation of waiting lines does not depend on the number of customers or servers, but rather on the variability of the demand and system capacity. Queueing theory is unlike other areas of operations research in that it does not determine optimal decision policies. Instead, it provides information about characteristics of waiting lines on which decisions about service capacity can be based. The performance measures of a queueing system used in this report assume the system is in a *steady state* condition, that is, the system has been operating for a period of time sufficient for the state of the system to become independent of initial conditions and elapsed time. Measures of queueing system performance at steady state typically include the expected number of customers in the queueing system, expected number of customers in the queue, expected time a customer spends in the queueing system and the expected waiting time a customer spends in the queue. Measures of particular interest in queueing models of human-machine systems include operator utilization, which has been used as a means of evaluating operator workload, and the expected waiting time of tasks in the queue. The probability of a particular number of tasks in a queueing system may be evaluated to examine the likelihood of tasks having to queue for attention.

2.1. Queueing Models of Operator Tasks

The basic process assumed by most queueing models involves customers arriving at a queueing system and, if no service mechanism is available, joining a queue to await service. Communication tasks in the aviation environment require service of a human operator who is classically modelled as a single-channel service mechanism that serially allocates attention to a variety of tasks. When the operator's attentional resources are available, tasks are selected for performance from the queue(s) with an order of precedence known as the *queue discipline*. The tasks are performed and subsequently leave the system. Figure 1 illustrates the aircraft communications queueing model in which a single operator is responsible for multiple tasks.

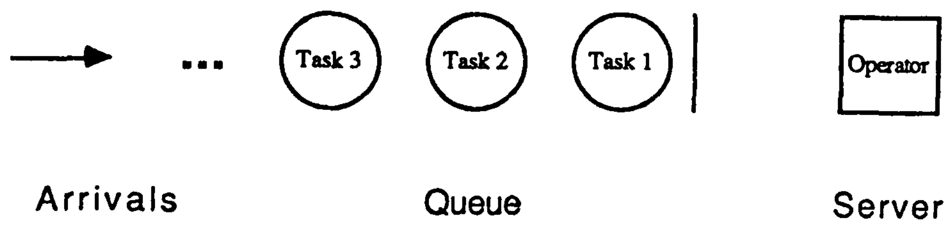

Figure 1: *Single-operator multiple task model*

There are four major elements of any queueing process:

1. input source;
2. queue length;
3. queue discipline; and
4. service mechanism.

Assumptions about these elements are necessary to completely describe a queueing system and must be incorporated in the model.

Input Source

The input source is the population from which tasks arrive and is characterized by its size. The size of the input source must be assumed to be either infinite, for example customers arriving at a bank, or finite, such as the number of machines in a job shop that may malfunction. The statistical distribution according to which tasks arrive at the queueing system from the input source must be specified. This distribution is known as the *interarrival time* distribution. Any unusual behaviour of tasks such as tasks not entering the queueing system when the queue length exceeds a maximum limit (*balking*) must be specified.

Queue Length

The maximum number of tasks queueing for service may be limited by, for example, the communication equipment or the capability of the human operator to recall the tasks to be performed, and must be specified or assumed infinite.

Queue Discipline

The order in which tasks are selected from a queue(s) for service typically are first-come, first-served or priority service disciplines.

Service Mechanism

The statistical distribution by which tasks are performed must be specified. This distribution, known as the *service time* distribution, can be determined from the times required to perform the tasks. The service facility under examination and the number and type of parallel service channels must be described.

2.2. Solving Queueing Models

The characteristics required to completely describe a queueing system often lead to ambiguity in the notation used by many authors. In 1971, a conference on Standardization of Notation in Queueing Theory (Phillips, Ravindran and Solberg 1976) agreed to classify queueing systems by a standard notation (see Appendix I).

Given a queueing system of particular interest, for example (M/M/1/∞/∞/FCFS), a queueing model is solved by determining the values of ρ, L_q, L, W_q and W which are the principal performance measures of the system. To model a queueing system, one can sample interarrival and service times from a real world system. The interarrival time distribution is characterized by the parameter $1/\lambda$, which is the mean interarrival time (time between arrivals). Similarly, the service time distribution is characterized by the parameter $1/\mu$, which is the mean service time.

The utilization rate, ρ, is determined by the interarrival and service rates of the system and evaluates the ability of the queueing system to meet its current demand. If $\rho > 1$, the demand on the system will exceed its capacity and the queue(s) will increase unceasingly. Typical performance measures cannot be evaluated analytically if $\rho > 1$, as no deterministic solution exists because of the system's instability.

The (M/M/1/∞/∞/FCFS) system is the most straightforward queueing model and can be solved analytically. The Markov property of the arrival and service rates assumes that the distributions are negatively exponentially distributed and characterized by the parameters λ and μ respectively. The model assumes arrivals and service completions occur one at a time, that is, no simultaneous arrivals may occur and tasks are performed serially.

3. LITTON SYSTEMS CANADA LTD. - CP-140 COMMUNICATIONS DATA

The purpose of the Litton study was to assist in defining a communication management system by analyzing both the crew system operation and the maintenance design requirements. Part of this goal was achieved by obtaining data about the functional requirements of the CP-140's communication management system during all major phases of a typical mission including:

1. system preparation;
2. take-off;
3. climb;
4. cruise out;

5. perform mission;
6. cruise back;
7. descend;
8. land; and
9. taxi/park.

The communications required during the perform mission phase of each type of tactical mission were moderately diverse. The remaining major phases, however, were more homogeneous in their communications patterns. Litton Systems selected the co-op mission for detailed examination as it required the greatest communication system usage. The purpose of a co-op mission is anti-submarine warfare during which the CP-140 Aurora operates jointly within a tactical group typically consisting of a helicopter, a ship with a towed array sonar system, a lead ship with the Officer in Tactical Command (OTC) and Force Air Control Officer (FACO), and an Eagle Control ship.

The NAVCOM tactical position, which will be the major focus of the queueing investigation, appears to be the most highly loaded in terms of communication system usage, particularly during the perform mission segment of the co-op mission. The communication system equipment typically used by the NAVCOM includes:

1. intercommunication set;
2. communication system control group;
3. VHF AM and FM radio sets;
4. UHF radio set;
5. HF radio sets (2);
6. radio teletype;
7. crypto devices;
8. data link;
9. radio navaids; and
10. VHF (AM) guard channel receiver.

Communications on the UHF/HF radio sets and the radio teletype can be either plain or covered voice.

To evaluate the applicability of queueing theory for predicting operator performance and workload, the NAVCOM operator is considered in his role of performing multiple tasks. The NAVCOM operator is responsible for all communications with the OTC/FACO to receive tasking and to transmit tactical messages. Mission activities are co-ordinated by him through communication with outside centers such as the Base Operation Center and the Maritime Operations Center. He is also in constant communication with the other tactical crew members and is responsible for all onboard communications, routine navigation and communications with all members of the tactical group. The NAVCOM will be considered as a single-channel processor who allocates his attention among the various tasks required of him.

Part of Litton's study consisted of a workload analysis that was performed by having NAVCOM operators rate each task of a typical co-op scenario on the basis of:

1. workload - how hard the operator had to work at each task;

2. criticality - how important it was to complete each task;

3. continuity - the extent to which the task could be time shared with another or interrupted;

4. difficulty - how hard the task was to perform, for example because of interface with equipment; and

5. frequency - how often the task was performed relative to other tasks.

An example of workload responses for the first phase of the mission is illustrated in Appendix II. Results of this analysis showed that the NAVCOM operators did not perceive the individual tasks to have high workloads, however, the operators indicated that they were heavily tasked during the period from when a target was sighted until it was neutralized and moderately tasked when the CP-140 Aurora was coming on-station.

Litton used the results of the workload analysis to construct a time-line analysis of the same co-op mission. Seven NAVCOM operators were surveyed to estimate the duration of each task and when each would occur in relation to the pre-established times for the start of the major mission phases. A summary of time-line responses for the first phase of the mission is illustrated in Appendix III. Litton used these summary data to produce a time-line analysis (see Appendix IV) to illustrate the periods of high utilization of the NAVCOM operator's attention and resources.

3.1. Assumptions Concerning the CP-140 Data

A single-operator model assumes tasks arrive and require service of the operator. If the operator is available, he performs the task, otherwise the task must join a queue for attention. To model a single-server queueing system, the interarrival and service time distributions of tasks must be known. Service times may be readily observed, but the ability to observe arrival times is dependent on the type of task, and in many operational environments, only the time when tasks are performed may be observed. For example, the task of listening to an incoming communication arrives when the message commences. This type of task cannot queue for attention. It is either attended to by the operator or it is ignored. The time at which a task such as navigation arrives is not as clear. One can observe the time at which the operator performs the task, but not the time at which the navigation task was originally required. It is unclear whether the time-line analysis data collected by Litton reflect the demand of the system on the operator, which would represent arrival times, or the times at which the tasks start to be performed.

The data required to drive the single-server queueing model include the operators' judgements of the duration of each task (service time) and the time when each task would begin (assumed to be arrival time) The data were the original responses of the seven operators to the time-line analysis survey that Litton summarized in Appendix III. The procedure of obtaining a single start and duration time for each task from seven estimates was complicated by the variation in the replies of the seven operators (see Table 1). A task was assumed to be performed if two or more operators indicated responses for that task. In many instances the replies of individual operators could not be quantified, as tasks were indicated as being performed intermittently or continuously without any duration estimates. The *median* of the commencement times was employed to obtain a single arrival time for each activity as the data had a high variance within observations of a single communication task and were also highly skewed.

Table 1: *Examples of operator responses*

NAVCOM No.								
Tasks	Time h	1	2	3	4	5	6	7
task a	start	0445			0450	0445	0445	
	duration	-		i	60	60	30	
task b	start	0500			0505	0505	0505	
	duration	-			10	60	60	
task c	start	[illegible]	0530	0500	0510	0505	0505	0500
	duration	300	60	60	60	60	120	120
task d	start	0510			0515		0510	
	duration	-			10		60	
task e	start	0510	0530	0505	0515	0505	0510	0520
	duration	300	60	60	60	20	15	30

- performed continuously
i performed intermittently

The following assumptions were required to extract the information necessary for a queueing analysis:

Input Source

The statistical distribution describing task arrival at a system may be determined from the interarrival times of tasks. It was assumed that the arrival times of the tasks to the system were the times at which the tasks were estimated to occur, as arrival times to the system could not be determined from the data. Although the effect of waiting in a queue for servicing was not considered, this assumption was necessary to establish an approximate interarrival distribution. The matter is complicated by the method in which the data were collected. NAVCOM operators indicated when tasks would occur within five minute intervals. It was arbitrarily assumed that servicing of a task began on the first minute of the interval. This assumption was made as *events*, which are occurrences that may change the state of a system, must occur at specific points in time to satisfy the conditions of a discrete event queueing model.

When applying queueing theory techniques, the input source is often assumed to be unlimited, even when the actual size is some large finite number. This is to simplify the calculations and is justified as the input source is not significantly affected by the number of tasks present in the system when the arriving population is large. For this preliminary analysis, the size of the arriving population was assumed to be infinite.

Queue Length

It was assumed that the maximum queue length was infinite as this is standard practice when applying queueing techniques, particularly when an upper bound exists that is large. It is possible that tasks may balk when the queue reaches a given length. For example, queue length may be limited by the number of tasks an operator can recall to perform. As the NAVCOM operators did not indicate that tasks are neglected, assuming that queue length was infinite seems reasonable.

Queue Discipline

The tasks of the co-op mission scenario were presented in a pre-defined chronology, hence only the order in which the tasks were serviced was known, not the strategy by which the tasks were selected for service. It was possible that the NAVCOM operators performed tasks on a priority basis, neglecting tasks such as navigation when crucial communications were required. The limitations of the data prevented the assessment this possibility, hence it was assumed that the NAVCOM operator performed the tasks on a first-come, first-served basis.

Service Mechanism

The service mechanism under consideration was the communications facility of the NAVCOM station and is most simply modelled as communication and navigation tasks requiring service, joining a single queue and waiting to be performed serially by the NAVCOM operator. The NAVCOM is considered the service mechanism or server who allocates his attention to the required tasks.

The statistical distribution describing the service times of the tasks can be determined from the subjective estimates of the time required to complete each task. It was observed that estimates of time required to complete tasks were generally in multiples of five or sixty seconds (see for example, service times in Table 2). The most extreme estimate was utilized in all instances where an operator indicated two conceivable durations for a single activity. These assumptions were made to establish upper limits on the communication system requirements. The median of the seven estimates was used as a service time as again, the data had a high variance within observations and were also highly skewed. Potentially, distinctive types of tasks may be modelled by different service distributions, but it was assumed that all types were of the same distribution because of the limited nature of the data.

4. ANALYSIS OF NAVCOM COMMUNICATIONS DATA

To evaluate performance measures of any queueing model, the system under consideration must satisfy steady state conditions, that is, tasks must arrive and be serviced according to a stationary stochastic process. A typical co-op mission is composed of several stages, each with a different purpose and category of activities. Intuitively, a segmented mission does not satisfy the same equilibrium conditions as it progresses through its entire course. For example, a NAVCOM operator would be expected to be considerably more active when initiating a coming on-station sequence than during a cruise-out period. Indeed, a visual inspection of Litton's time-line analysis (see Appendix IV) shows that ρ varies during each of the mission segments for the co-op mission, indicating changing arrival and service rates.

The purpose of the queueing analysis was to evaluate the ability of the model to predict the demand on the system. Three major mission segments were evaluated based on the criteria of the stability of the system, operator utilization, and, if stable, the probability of tasks having to queue for attention. The segments chosed covered a range of workload intensity levels and the tasks during each segment, from a visual assessment of Litton' time-line, appeared to arrive at randomly varying intervals and occur with constant average service times. The mission segments were:

1. (0414-0511)h Target-Fixed - Debris Sighted extremely busy period;

2. [0200-0230)h Coming Onstation — moderately busy period; and

3. [0115-0200)h Cruise Out — slow period.

The segments are identified in ZULU time from the beginning of the mission. Square brackets indicate tasks occurring during the period inclusive whereas round brackets indicate all tasks up to but not including the identifying time.

4.1. [0444-0511]h Target Fixed - Debris Sighted

According to Litton's time-line (see Appendix IV), the segment of the mission including target fixed passively until after neutralization when debris were sighted, is the period of the highest volume of communications for the NAVCOM operator. The tasks that would be performed during [0444-0511]h (see Table 2) were used to calculate the interarrival and service rates. ρ for the NAVCOM operator was evaluated as 1.7. Since $\rho>1$, the queue would continually grow and the system would never reach a steady state condition. The operator would be unable to perform the tasks according to the assumptions of the model, thus no deterministic solution exists.

As the operators were assumed to be capable of performing the tasks they claimed, the data were re-examined. Variation in the replies of the operators became apparent. Many claimed to neglect activities such as controlling and monitoring the aircraft systems and communications, navigation and homing, and the microphone/monitor select function. Eliminating these three types of tasks most operators claim they do not perform, (see Table 2), ρ continued to exceed unity. Performance measures were not calculated, as a queueing system which does not reach steady state does not have an analytical solution.

4.2. [0200-0230)h Coming On-Station

A segment involving fewer communication tasks was examined to determine if queueing techniques could be used to realistically model operator workload when tasking was at a moderate level. This criterion was met while the CP-140 performed a coming on-station scenario, [0200-0230)h (see Appendix IV). The tasks that would be performed during this period (see Table 3) were used to calculate the interarrival and service rates. The system would never reach a steady state condition as ρ was 1.9.

The NAVCOM operators testified that they would be moderately loaded during this period, but capable of performing their duties. A time-line of the combined operator responses during the period [0200-0230)h was constructed to determine if the model was accurately predicting the potential state of the system (see Appendix V). The time-line illustrated that the operators claimed to perform some tasks simultaneously that physically were not possible, for example, voice communications of two different messages performed on two different frequencies simultaneously. Time-lines for individual operators were constructed to determine if the actions described in individual replies could be performed (see Appendix V). Even individual operators, however, claimed simultaneous performance of some tasks that were not possible.

As the NAVCOM operator would have been able to complete his tasking, the system should reach a steady state. However, ρ indicated that steady state would not be reached, according to the assumptions of the model. It was presumed that the data did not accurately reflect the tasks that were completed in the real system, thus a model based on these data would also be inaccurate.

Table 2: *Interarrival and service times of tasks during [0444-0511]h*

Target Fixed - Debris Sighted [0444-0511]h		
Service Time (s)	Arrival Time (ZULU)	Interarrival Time (s)
120	*445	0
120	*445	0
120	*445	0
60	445	0
75	445	300
60	450	0
90	450	300
120	455	0
90	455	0
60	455	300
60	500	0
120	500	0
60	500	300
75	*505	0
40	*505	0
25	*505	0
60	*505	0
60	505	0
38	505	0
35	505	0
60	505	180
60	*508	0
180	508	0
60	508	120
120	*510	0
60	*510	0
60	*510	0
60	*510	0
60	*510	0
120	510	0
120	510	0
45	510	0
60	510	60
30	511	120
60	513	0
150	513	120
25	515	0
20	*515	0
30	515	0
180	515	-

* less than three operators claimed to perform this task

Table 3: *Interarrival and service times of tasks during [0200-0230)h*

Coming On-Station [0200-0230)h		
Service Time (s)	Arrival Time (ZULU)	Interarrival Time (s)
180	208	0
30	208	120
60	210	180
120	213	0
120	213	120
600	215	180
120	218	0
600	218	120
60	220	300
45	225	0
105	225	0
85	225	-

4.3. [0115-0200)h Cruise Out

The segment during which the CP-140 would be in transit to the mission area was examined, as this period has low communication requirements for the NAVCOM operator. The tasks that would be performed during [0115-0200)h (see Table 4) were used to calculate the interarrival and service rates. The system would reach steady state as ρ was 0.7. This indicates the operator was occupied 70 percent of the time.

Table 4: *Interarrival and service times of tasks during [0115-0200)h*

Cruise Out [0115-0200)h		
Service Time (s)	Arrival Time (ZULU)	Interarrival Time (s)
180	115	0
30	115	0
180	115	300
180	120	180
75	123	120
60	125	300
120	130	180
60	133	420
270	140	-

The time-line of transformed data (see Appendix V) illustrated that the operators would be capable of performing the tasks sequentially within the given time frame and that they would be occupied approximately 65 percent of the time. These transformed data were assumed to represent the real system as the queueing and time-line analyses indicated similar utilization percentages of operator time. The data were used to determine the input parameters for the queueing model ($M/M/1/FCFS/\infty/\infty$) described earlier.

The number of tasks was insufficient to select input probability distributions of interarrival and service times with confidence. Histograms of both data sets (see Figure 2) did not appear representative of frequency distributions typical of these applications. Tasks that arrive randomly

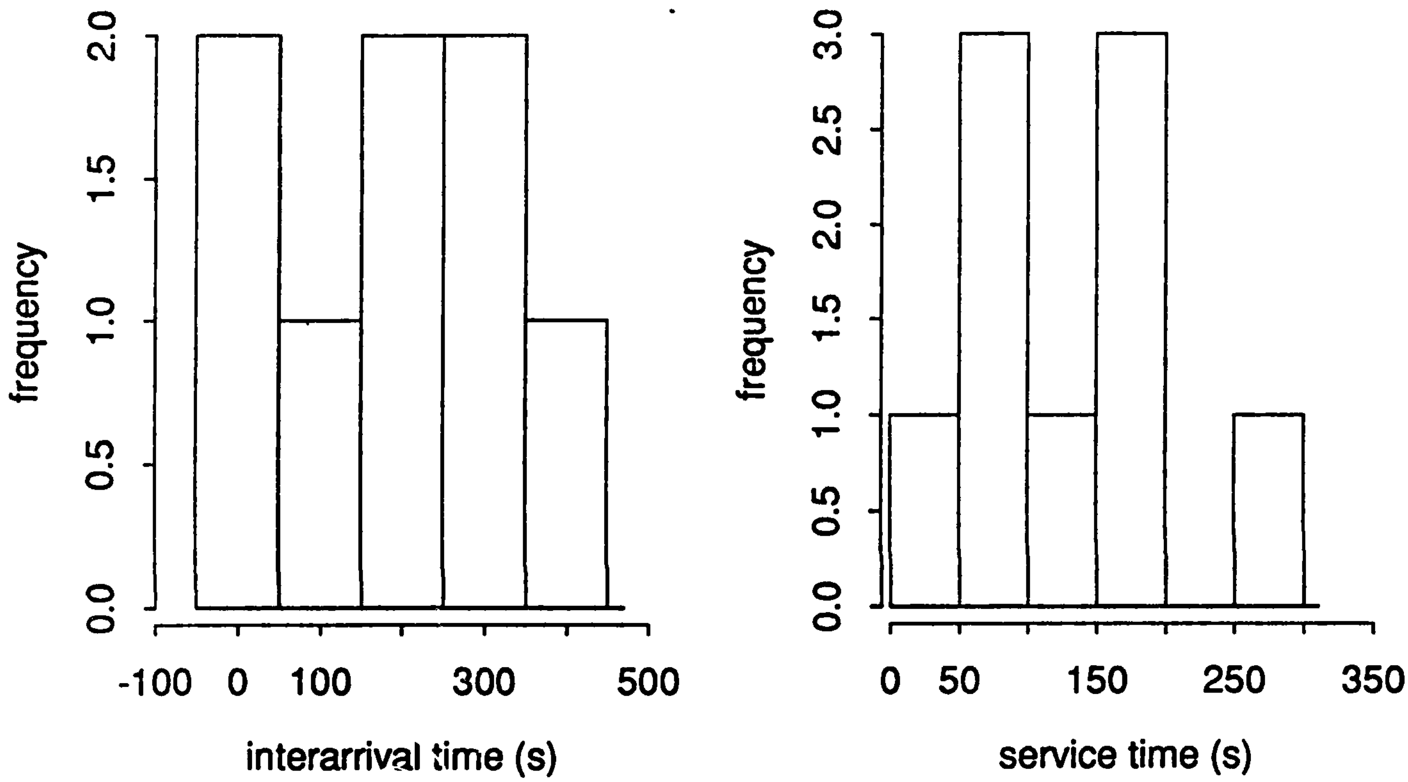

Figure 2: *Interarrival and service time histograms*

with a constant average are said to follow a Poisson process and although few activities arrive in a true random fashion, they may appear to do so when scheduled tasks arrive independently of other types of scheduled tasks. It is reasonable to assume that the navigation and communication tasks required of the NAVCOM operator would follow a Poisson process. Because of this assumption and because exponential distributions are typically used to model times between arrivals at a service facility (Law and Kelton 1982), the arrivals were assumed to follow an exponential distribution. The mean time between arrivals was used as the estimator of the scale parameter of the interarrival distribution. An exponential service time is implied if the amount of time required for completion of a task is independent of how long a task has been in the process of being performed. Exponential service distributions are typically used to model service times when the mean and standard deviation of the data are approximately equal (Rouse 1980). As the service data of the NAVCOM operators satisfied these criteria, the data were modelled as exponential with the mean as the estimator of the shape parameter. The NAVCOM operator was assumed to be the only server, tasks were assumed to be performed on a first-come, first-served basis and both the task population size and the maximum number of tasks allowed in the system were both assumed to be infinite.

Typical performance measures of the (M/M/1/FCFS/∞/∞) system were calculated:

$$L = 2.2 \text{ tasks}$$

$$L_q = 1.5 \text{ tasks}$$

$$W = 407 \text{ s}$$

$$W_q = 278 \text{ s}$$

The probability of more than one task in the queueing system (ie. the probability of a task having to queue for attention) was 0.46.

5. DISCUSSION

Queueing models of human operators in multi-task situations have classically been based on the assumption that humans are single-channel processors, that is, tasks are performed one at a time. Welford (1960) sketches the historical development of work in the area of man's information processing capabilities. He suggests an apparent single-channel in a human's central mechanism that deals with signals or groups of signals serially so that signals coming in rapid succession may have to queue before they are attended to. Models of this type include Schmidt's (1978) air traffic control model and Rouse's (1980) flight management model. It follows that a single-channel queueing model was a reasonable point at which to begin this investigation. The intent is to assess the limitations and assumptions that must be made when applying queueing theory to human-machine interaction in general, not to develop a finely tuned model.

Sources of error in applying queueing theory to Litton's original time-line analysis survey could originate from assumptions of the queueing model or from the data required to drive the model. The assumptions necessary to describe the queueing system were based on Litton's original data. Although the data were not intended for the application of queueing theory, a preliminary examination using Litton's summary data (Beevis 1988) indicated the data were potentially useful. The results of these calculations indicated the system was stable during two periods of varying activity levels assuming a single-channel model and appropriate arrival and service distributions. These calculations, however, were based on Litton's summary data which did not appear to map consistently to the original data. The models in the present report were based on the original data. For the purposes of this study, the subjective responses of operators were assumed to accurately represent tasks that are actually performed. The input population was assumed to be a single source of infinite size but it is possible that more than one arriving source exists. For example, a potential model could involve arriving external and internal tasks as well as navigation tasks such as monitoring and controlling. As the number of communication tasks are not limited by the device used, the population size was assumed to be infinite. For example, a message can be received on a radio regardless of whether a different message had just been received on the same set. Although, the frequency distributions of both the interarrival times and service times could not be evaluated statistically because of the limited number of responses, each was assumed to follow a distribution typical for its application, i.e., an exponential.

The queue length was assumed to be infinite. If operators rely on memory and tasks arrive frequently, it is possible that only a limited number of tasks could be recalled. Task shedding would occur and a limited queue length would be implied. The order in which the tasks to be performed were selected from the queue was assumed to be on a first-come, first-served basis. It was difficult to determine how the queue discipline should be modelled from Litton's data as tasks were specified in a pre-defined order without indicating optimal performance times. It is most likely that tasks are performed on a priority basis such as a navigation task that must be performed hourly. The task may enter the system with a top priority at its appropriate service time. If the task could not be serviced immediately, it would join the queue and its priority would increase the longer it waited. Similarly, communication tasks could be assigned priorities by external sources or by operating procedures. The problem of determining how tasks are selected from the queue leads to the consideration of how scheduled tasks such as monitoring, controlling, and navigation should be modelled.

The analysis of the highly loaded segment [0444-0511]h using a serial task processing model suggested that the system would not reach steady state. Operators verbally reported that this segment was the most severe in terms of communication requirements, thus the system may have existed in a non-equilibrium state. Similarly, the analysis of the moderately loaded segment [0200-0230)h suggested that a non-equilibrium situation existed, however, verbal reports indicated that the operators were capable of meeting the demand placed on them by the system. Independent subjective ratings of workload during the cruise-out period show ratings of 1 out of 5, indicating a low workload requirement. An analysis of the time-line data using the exponential model indicates that operators are utilized 70 percent of the time which is suspiciously high for a slow period. Figure 3 illustrates the relationship between the expected number of tasks in the queue and operator utilization. For utilization rates of greater than 70 percent, the expected number of tasks waiting will be large. It is thought that tasks queueing for an operator's attention would load the operator, hence a utilization rate of 0.7 would not be perceived as low workload.

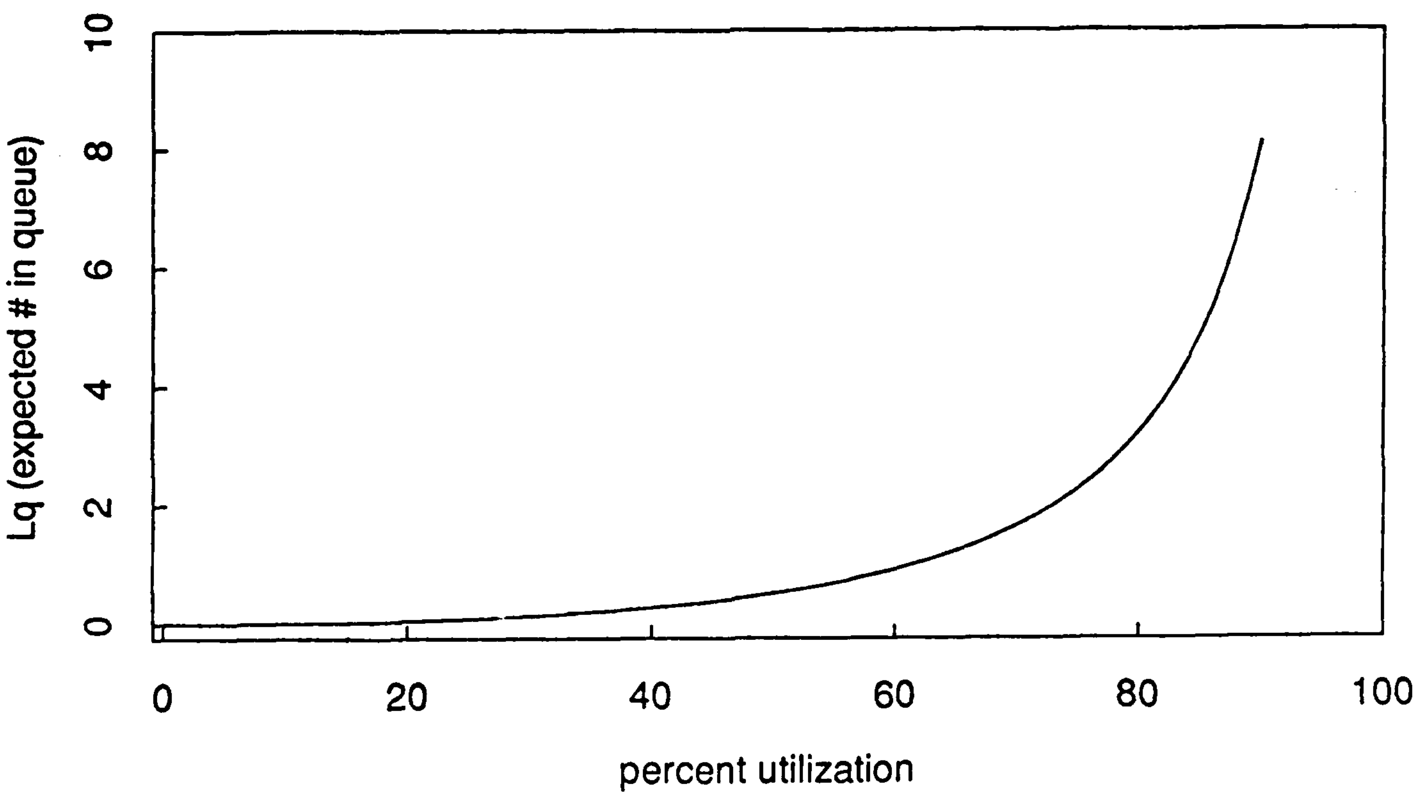

Figure 3: *Expected number of tasks in queue vs utilization*

The expected waiting time in the system and the queue and the expected number of tasks in the system and the queue were calculated for the segment [0200-0230)h with low workload. These predictions could not be compared to any measured performance evaluation as the arrival times to the system were unknown. The number of tasks waiting to be performed by the operators would not exceed five approximately 90 percent of the time. Conversely, six or more tasks would queue ten percent or more of the time which seems like an unreasonably large quantity of customers for a period of low workload. The results of the queueing model seem unreasonable which may be due to the subjective nature of the data collection method or because of invalid assumptions of the model.

One concern for the suitable application of Litton's data was the inaccuracy of the operators' judgements. Seven operators provided estimates of the duration of each task and approximately when each would occur during a typical co-op mission. Often pages of an operator's survey would be one hour ahead or behind other operators. The tasks were presented in a specific chronology and operators could indicate when tasks would occur only during five minute intervals. Many of the NAVCOMs were concerned about the pre-defined order of the activities and responded to monitoring and controlling tasks with comments such as the task was performed intermittently or continuously. It is questionable whether the elemental breakdown of tasks was of a sufficiently low level to be used for a queueing application. Commencement of tasks could only be indicated within intervals and assumptions had to be made regarding specific start times. Hence, if two tasks started during the same interval, it was assumed that the two tasks occurred simultaneously, even though this may not have been the situation the operator had intended to portray. Simultaneous activities violated the assumption that arrival and service times were independent and identically distributed random variables. It was necessary to combine the data to obtain a single occurrence time and duration for each task. This procedure, although based on justifiable assumptions, was suspect because of the variation in operator replies. For example, some operators claimed to perform tasks that others did not and some indicated start times without corresponding durations.

The subjective method by which the data were obtained appeared to be the major limitation in its potential application to queueing models. Time-lines of the combined responses indicated that the NAVCOM operators claimed to perform simultaneous tasks that were not physically possible. This may have been due to the assumptions used to transform the data, however, time-lines of individual operators illustrated this same claim (see Appendix V). The data do not accurately represent the real world situation. Wickens (1984) cites two studies concerning the retrospective estimation task in which subjects are asked to estimate the amount of time required to complete a task. The first study found that times were underestimated when tasks were difficult choice reaction time tasks or memory tasks. The second study, using aviation tasks, observed that times were overestimated. Although the knowledge of time estimation appears uncertain, the application to aviation tasks suggests a possible explanation for discrepancies in the data. The duration estimates always appear as multiples of five or sixty seconds. The level of the task analysis requires more accurate time estimates to be consistent with reality. The operators may have been estimating times to their best ability or the data may reflect what the operators believe they do or what they should do, not the tasks that are performed.

Classically, human operators have been modelled as single-channel processors who serially allocate attention or resources to a variety of tasks. During the moderately loaded segment [0200-0230)h, the utilization of the operator was evaluated as much greater than one hundred percent, however, the operator can achieve satisfactory performance on all required tasks. The performance of simultaneous activities may explain how the operator appears to service all activities requiring more time than that available. A more suitable model of the human operator may include several channels or modalities and indeed the attention literature supports the theory of the human, who as a multiple-channel processor, can perform separate activities requiring attention and resources of two different modalities simultaneously without interference (Kerr 1973). An objective study of operator performance may more accurately reflect the types of activities that are performed simultaneously.

6. CONCLUSIONS AND RECOMMENDATIONS

The examination of Litton's communications data provided insight into the limitations that exist and assumptions that must be made when applying queueing theory to an individual performing multiple tasks. The method of data collection by which operators estimate the time of occurrence of tasks during five minute intervals and the durations of these tasks has proven useful for the identification of peak workload periods of a mission. The application of data collected by this technique to queueing models, however, has not been satisfactory. It is apparent from the responses of operators that humans are not particularly good at estimating the time it takes to perform tasks. This resulted in reports of tasks being performed concurrently that physically are not possible. Although it is doubtful that Litton's data accurately reflect single tasks performed by a NAVCOM operator, responses show that individuals may perform more than one task at a time. The fundamental single-server model that was applied to the data assumes that tasks are processed serially, but the analysis indicates that a more sophisticated model of human performance is required to apply queueing theory to a multi-task system. Because of the limitations of both the subjective survey technique of time estimates and the single-channel queueing model of operator performance, a method of objective data collection and a new multiple channel model are recommended.

A potential model of a NAVCOM operator would include three parallel servers: voice (speaking), auditory (listening), and motor (physical movement) channels, each representing a modality of observable human behaviour. The term parallel signifies that each server would act independently of the others implying simultaneous activities may occur. The model takes into consideration behaviour typical of NAVCOM operators, such as listening to an incoming communication while referring to a navigation aid. Independent stochastic processes corresponding to each modality would drive the model and each process could be divided based on its source. For example, the auditory modality could be driven by the two independent sources of external and internal communications.

Clearly the type of data required for the analysis of this type of queueing model is of a much finer level of detail than the task analysis produced by Litton, for example, the time required to perform observable tasks should be evaluated to the nearest second. One data collection method which is unobtrusive and relatively easy to employ is the empirically validated task analysis (EVTA) process. Audio/video equipment is used to collect a permanent record of operator activities after which the tape is analyzed by manually recording both the time at which each task begins and the duration of each task. The major benefits of this process is that the analyst can review how operators co-ordinate the performance of a set of tasks many times. The EVTA process has been used successfully to obtain an accurate representation of crew activity in support of the Canadian Forces Light Helicopter replacement project (Shaffer, Hendy and White 1988). The data were used to support workload prediction models for the project. Future research in the application of queueing theory to human-machine interaction includes investigating the potential multiple channel model with objective data, determined from the EVTA process, to evaluate human behaviour and operator workload.

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APPENDIX I

QUEUEING NOTATION

Standard queueing notation used to classify queueing systems:

(A/B/C/X/Y/Z)

A = Interarrival Time Distribution

B = Service Time Distribution

C = Number of Servers

X = Maximum Number of Tasks in System

Y = Size of Task Population

Z = Queue Discipline

Typical distributions used to describe ***interarrival*** and ***service*** times include:

M - Exponential (Markov)

E_k - Erlang-K

HE_k - Hyperexponential

D - Deterministic

Common *queue disciplines* include:

FCFS - first come-first served

LCFS - last come-first served

PR - priority

NPRP - non-preemptive priority

Symbols used to denote *interarrival* and *service* time characteristics include:

λ = arrival rate

$\frac{1}{\lambda}$ = mean time between arrivals

μ = service rate

$\frac{1}{\mu}$ = mean service time

ρ = utilization rate

$\rho = \frac{\lambda}{(c\mu)}$ where c = number of servers

Note:

$\rho < 1$ System reaches steady state. Operator busy ρ % of the time.

$\rho = 1$ Queue slowly becomes infinitely long. Operator will be fully occupied.

$\rho > 1$ System will have constantly increasing queue. Operator will be fully occupied.

Symbols of queueing system ***performance measures*** under ***steady state*** conditions include:

$L_q = \frac{\lambda^2}{\mu(\mu-\lambda)}$, Expected number of customers in a queue

$L = \frac{\lambda}{\mu-\lambda}$, Expected number of customers in a system

$W_q = \frac{\lambda}{\mu(\mu-\lambda)}$, Expected waiting time in a queue

$W = \frac{1}{\mu-\lambda}$, Expected waiting time in a system

Probability of n customers in the system at any time:

$$P(N=n) = P_n = (1-\rho)\rho^n$$

APPENDIX II

Appendix II is taken from the Operator Workload Analysis survey conducted by Litton Systems Canada Ltd. and is the first page of the response of a single NAVCOM operator. Tasks performed during a co-ordinated operations mission are listed sequentially in the left column. NAVCOM operators rated each task required of the NAVCOM on a scale from 1-7, on the basis of workload, criticality, continuity, difficulty and frequency. 1 was a low rating and 7 was a high rating.

CP–140 COMMUNICATIONS MANAGEMENT SYSTEM
OPERATOR WORKLOAD ANALYSIS

SQUADRON: 404/405/407/415 (CIRCLE ONE)   DATE: 7 Feb 76

POSITION: NAJCOM

TASK / DIMENSIONS	WORKLOAD	CRITICALITY	CONTINUITY	DIFFICULTY	FREQUENCY	ANALYST REMARKS
1.1 SYSTEM PREPARATION (0000 HRS)						
1.1.1 RX MISSION BFG						
1.1.2 RX PDIP DATA	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
1.1.3 RX ORDNANCE BFG	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
1.1.4 RX WX BFG	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
1.1.5 PERF FLT PLNG	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
1.1.6 ACCEPT A/C	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
1.1.8.1 CHECK ORDNANCE	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
1.1.8.2 PERF WALK-AROUND (APU PWR ON)	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
1.1.10 ACTIVATE A/C SYS	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
1.1.11 CONDUCT SYS CKS						
1.1.11.9 COMM WITH MTNCE (UHF PL VCE)						
1.1.11.9.3-6 SEL UHF CTLS FOR RX/TX	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
1.1.11.9.7 ACT TX-PASS MSGE	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
1.1.11.9.17-1.8 MON RX/TX ADJ VOL/SQ	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	

APPENDIX III

Appendix III is taken from the Time-Line Analysis Survey conducted by Litton Systems Canada Ltd. and is the first page of the combined responses of seven NAVCOM operators. Tasks performed during a typical co-ordinated operations mission are listed sequentially in the left column. For each task required of the NAVCOM, operators indicated when each would begin during a five minute interval and its duration.

CP-140 AURORA COMMUNICATIONS MANAGEMENT SYSTEM
FUNCTIONAL DESIGN REQUIREMENTS
TIME-LINE ANALYSIS SURVEY
COORDINATED OPERATION MISSION SCENARIO (REF: DIDS FA 1, 2 & 3)

SQUADRON: 404/405/407/415 (CIRCLE ONE)

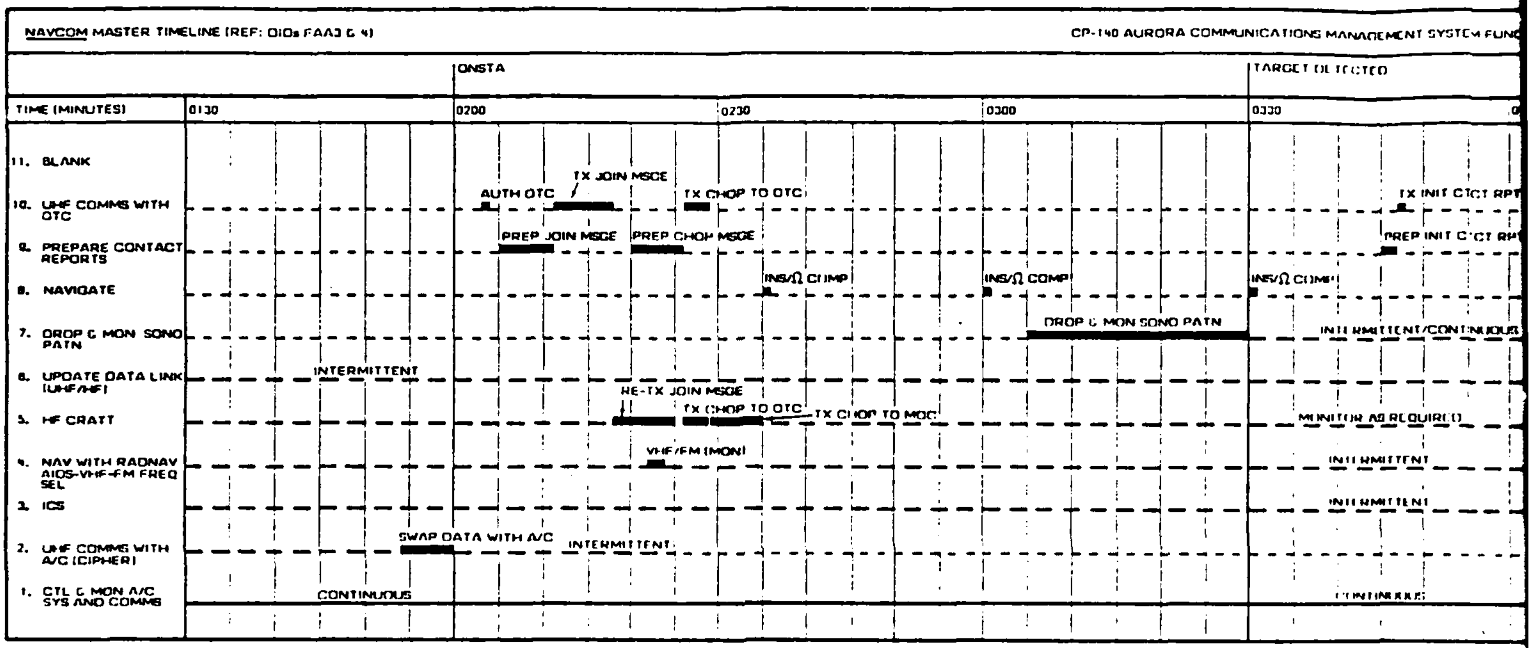
DATE: ____

POSITION: NAVCOM

TASK NO /TITLE	TIME-LINE 0000–0700 (05 10 15 20 25 30 35 40 45 50 55 per hour)	REMARKS
1.1.11.13 COMM WITH BOC (UHF CIPH VCE)		
1.1.11.13.2-13.6.2 SEL UHF CTLS FOR UHF CIPH VCE TX/RX	(2 SECS)	CREW UNABLE TO MONITOR CIPHER
1.1.11.13.7 ACT TX-PASS MSGE	(4 SECS)	
1.1.11.9.17-18.1 MON TX/RX-ADJ VOL/SQ	(20 SECS)	
1.1.9 PERF PRE-ST CK		
1.1.9.1 START ENGINES		MONITOR ALL EQUIP AND
		COMMS
1.1.9.2 PERF PRE-TAXI CK		
1.1.9.3 TAXI CK		
1.1.11.11.1-12 COMM WITH ATC (VHF AM PL VCE)	(10-15 SECS)	
1.1.11.10.1-10.4.1 MMSF WITH CREW	(AS REQUIRED)	MONITOR - LOG CLNCS
1.1.9.3.1 TAXI	(2 MIN)	
		FORMATTING "OUT" MSGE ON MPD
1.2 T/O (0100 HRS)		
1.1.9.4 PERF PRE-T/O CKS		
1.2 T/O		
1.2.1 POST T/O CK	(60 SECS)	MONITOR MMSF
1.2.1A CTL & MON A/C	CONTINUOUS →	TX "OUT" MSGE TO MOC
1.1.11.11.1-12 COMM WITH ATC (VHF AM PL VCE)		
1.1.11.10.1-10.4.1 MMSF WITH CREW	(20 SECS)	MONITOR
		PASS ETA'S TO FLT DECK CONDITION IV CHECKS

APPENDIX IV

Appendix IV is Litton's NAVCOM Master Timeline that summarizes the responses to the time-line analysis survey of seven NAVCOM operators. The X-axis indicates the time as the mission progresses and the Y-axis indicates ten major activities of the NAVCOM position. The time-line shows when the operator would be engaged in each type of activity and the types of activities that are performed simultaneously.



ACTIVIVTY LEGEND: (Y-AXIS)

1. CONTROL AND MONITOR AIRCRAFT SYSTEMS AND COMMUNICATIONS -
   - CONTINUOUS ACTIVITY
   - DEPENDING UPON CREW STATION AND CREW PROCEDURES INCLUDES MONITORING OF:
     - -ALL RADIO SYSTEMS
     - -ALL ENGINE SYSTEMS
     - -ALL FLIGHT CONTROL SYSTEMS
     - -ALL NAVIGATION SYSTEMS
     - -ALL OTHER ACTIVITIES THAT REQUIRE "CONTROLLING AND MONITORING"

2. UHF COMMUNICATIONS WITH AIRCRAFT
   - INTERMITTENT ACTIVITY WHEN ON PLAIN VOICE
   - CONTINUOUS ACTIVITY WHEN USING CIPHER CAPABILITY
   - INCLUDES LOGGING OF ALL VOICE COMMUNICATIONS WHEN TACTICAL SITUATION DICTATES
   - ALSO INCLUDES DICASS ACTIVATION

3. INTERCOMMUNICATIONS (ICS)
   - INTERMITTENT ACTIVITY, SOMETIMES NEAR-CONTINUOUS BY CERTAIN CREW MEMBERS
   - IMPORTANT TO NOTE THAT WHEN MONITORING AND TRANSMITTING ON CIPHER, OPERATOR ISOLATED FROM ALL OTHER COMMUNICATIONS AND REQUIRES LISTENING TO SPEAKERS CONTROLLED BY OTHER CREW STATION (WHICH REQUIRES REMOVAL OF ONE EARPHONE - THEREFORE HELMETS NOT USED)

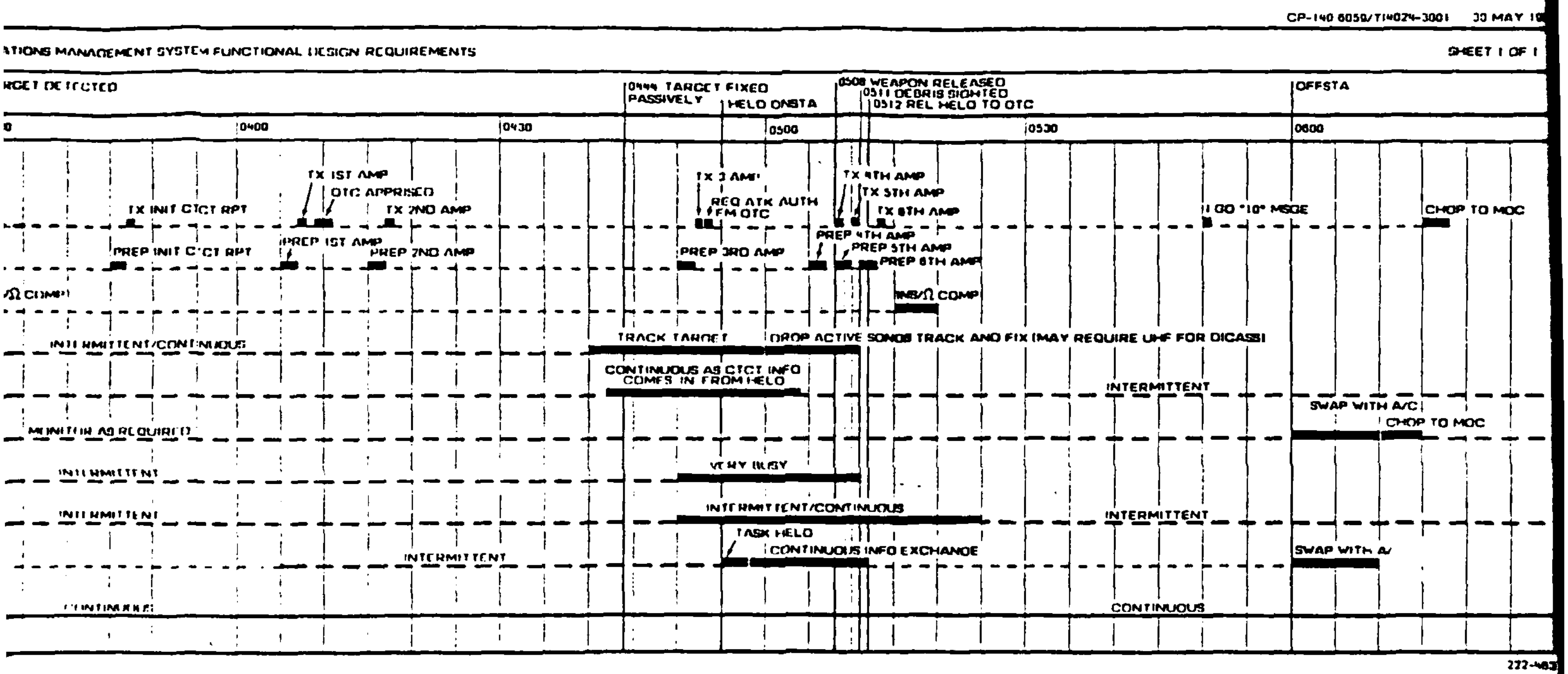
4. NAVIGATION AND HOMING
   - INTERMITTENT ACTIVITY
   - INCLUDES MONITORING, LOGGING OF INS/OMEGA
   - INCLUDES VHF-FM SONOBOUY FREQUENCY SELECTION

5. HF CRATT
   - INTERMITTENT TRANSMISSION ACTIVITY
   - CONTINUOUS MONITORING ACTIVITY

6. DATA LINK
   - CONTIN
     THE OR
   - INTERM
   - PERIODI
     REQUIRE

7. DROPS AND M
   - PERIODI

8. NAVIGATE (E X
   - PERIOD
   - INCLUD
   - INCLUD
     TACNAV



6. DATA LINK
- CONTINUOUS MONITORING ACTIVITY THAT COULD UTILIZE HF OR UHF SET CONTINUOUSLY
- INTERMITTENT INFORMATION INSERTION REQUIRED
- PERIODIC PURGING REQUIRED AS INFORMATION AND SYSTEM REQUIREMENT DICTATES

7. DROPS AND MONITORS SONOBUOY PATTERN
- PERIODIC SELF EXPLANATORY ACTIVITY AS TACNAV DICTATES

8. NAVIGATE (EXECUTE MANOEUVRES)
- PERIODIC/CONTINUOUS ACTIVITY AS TACTICAL SITUATION DICTATES
- INCLUDES INS/OMEGA NAVIGATION (OTHER THAN COMPARISONS)
- INCLUDES FLYING AIRCRAFT AS DICTATED BY TACNAV (INCLUDING SONOBUOY HOMING)

9. PREPARE CONTACT REPORTS
- PERIODIC ACTIVITY
- INCLUDES EXCHANGE OF INFORMATION TO FACILITATE REPORT PREPARATION

10. UHF COMMUNICATIONS WITH SHIPS
- PERIODIC ACTIVITY WITH OTC/FACO/ASWCS ETC.
- INTERMITTENT ACTIVITY WHEN USING PLAIN VOICE
- CONTINUOUS ACTIVITY WHEN USING CIPHER CAPABILITY

11. ANALYSE DATA, SELECT TACTICS & SENSORS, INSTRUCT CREW

Figure 2-1 NAVCOM Master Timeline

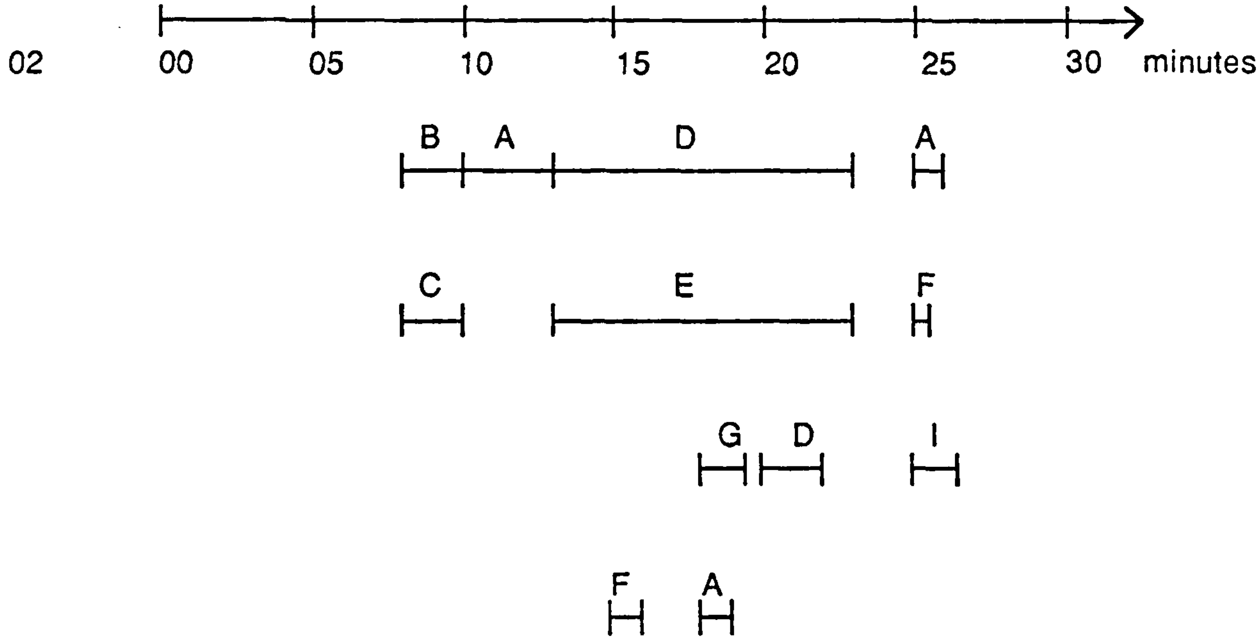
APPENDIX V

Appendix V illustrates time-lines of NAVCOM operators' responses for specific periods of a co-op mission. The data used for the analysis were the raw data taken from Litton's time-line analysis survey. The tasks an operator would perform were listed in a straight line when possible, but when more than one task was done at the same time, new lines were created. The lines show the number and types of tasks the operators claim to perform concurrently, according to the survey responses.

TIMELINE CODES

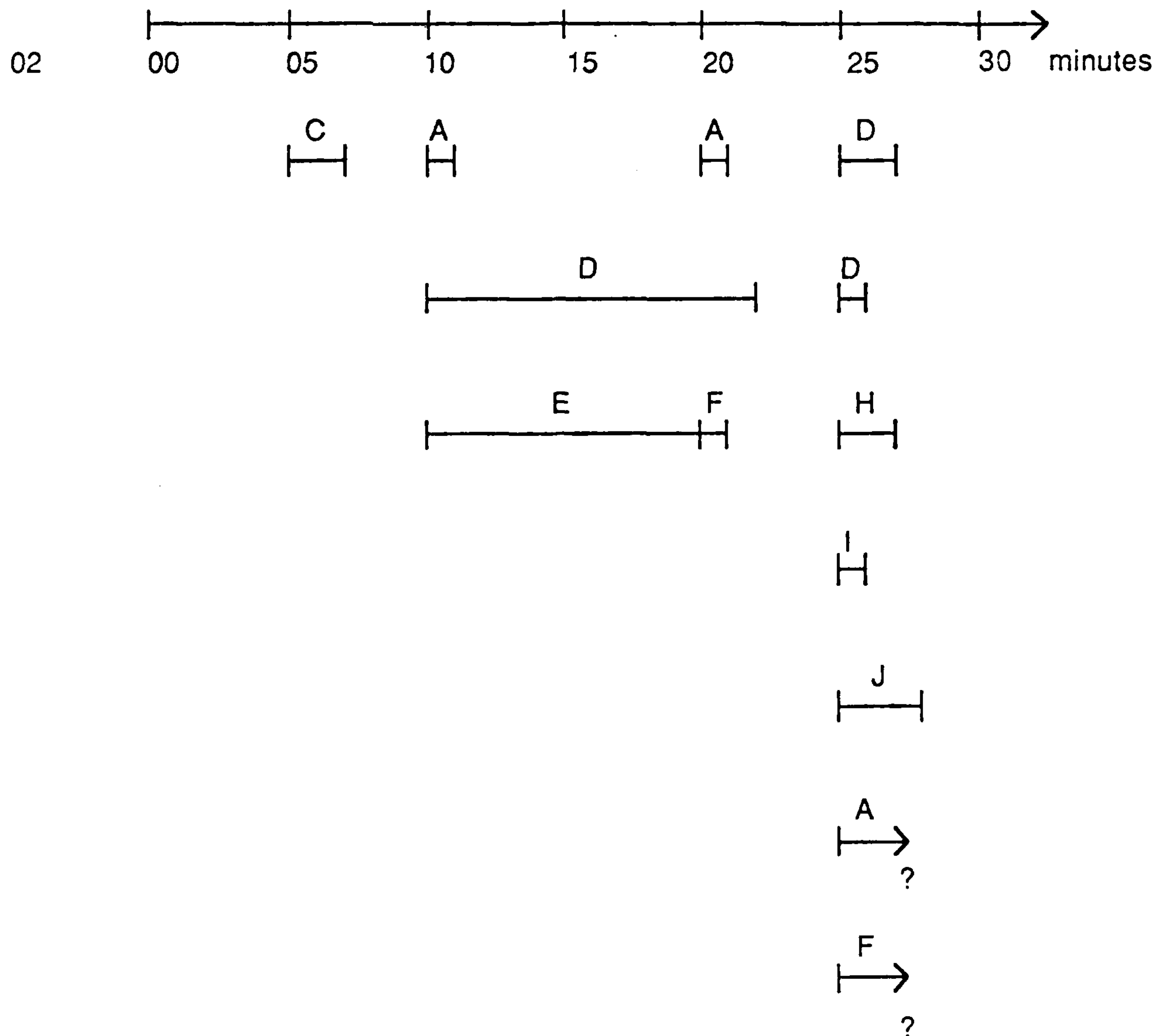
A	CTL & MON A/C SYS & COMMS
B	EX PRE PLANNED MANEUVERS
C	SWAP DATA WITH A/C (UHF PL VCE)
D	UHF/HF CRATT ONLINE OR UHF/HF PL/CIPH VCE
E	HF PL/CIPH VCE
F	MMSF WITH CREW
G	NAV A/C WITH RAD NAV AIDS
H	SEL CTLS FOR UHF/HF CIPH/PL DL
I	DL ACT-CONTINUOUS
J	NAVIGATE
K	COMM WITH ATC (VHF AM PL VCE)
L	SEL CTLS TO RX HF/UHF CIPH/PL DL
M	VERIFY SMRY GOOD ON MPO

[0200-0230)h Coming On-Station



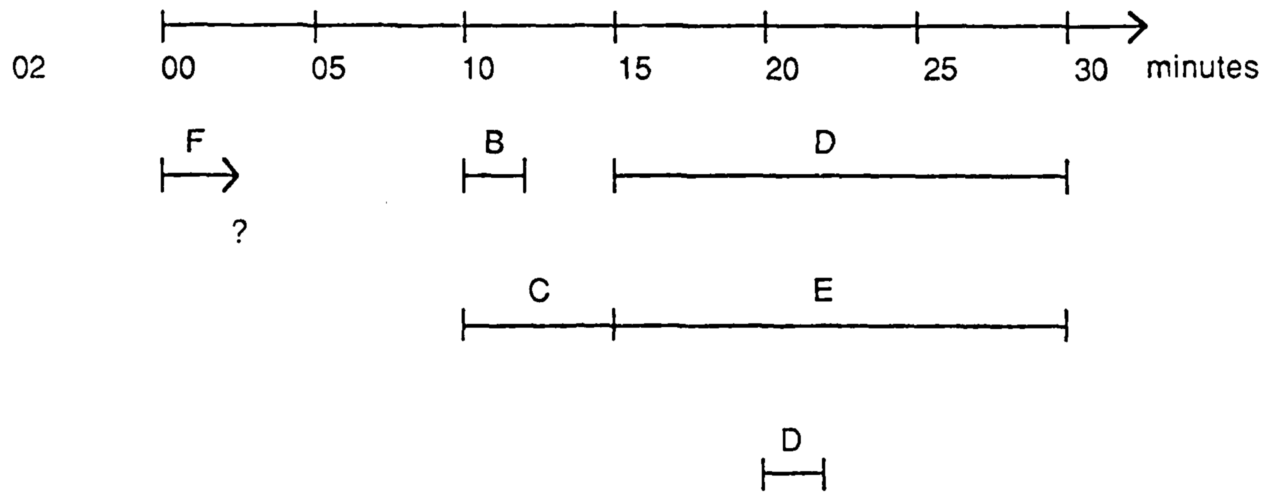
[0200-0230)h Coming On-Station

Operator #1

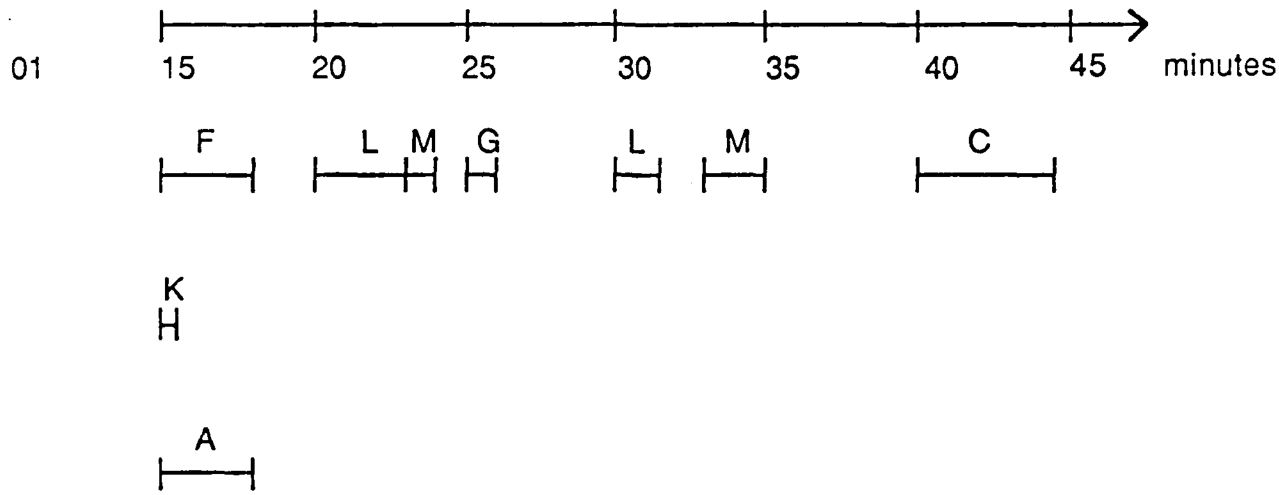


[0200-0230)h Coming On-Station

Operator #2



[0115-0200)h Cruise Out



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Several authors have argued that queueing models can be used to predict workload and performance of operators under the single-channel hypothesis of man's information processing capability. This paper investigates the application of queueing theory to communication and navigation tasks performed aboard the CP-140 Aurora using a simple exponential, single server model. It was anticipated that the model would provide insight into how individual tasks with low workloads combine to create high workload situations. The results, however, demonstrate that problems exist, which could originate from either the data or the model. A new model is recommended as well as the form of data required for applying queueing techniques.

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